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Original Article

Analysis of Single- and Multiple-Slotted Antennas for Wireless Applications

Gowri Chaduvula[1], B. Leela Kumari[2]

[1]*ECE Department, GIET, Andhra Pradesh, India.*
[2]*ECE Department, JNTUK, Andhra Pradesh, India.*

[1]*Corresponding Author : gowrich.ece@gmail.com*

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Abstract - *Conventional microstrip patch antennas are not suitable for modern wireless applications because of their low gain, low directivity, and poor radiation performance. To address these limitations, the patch antenna containing single- and multiple-slots is studied from the perspective of improving performance and its suitability for modern wireless applications. Further, studies were carried out on various slot configurations. The simulated results show that patch antennas containing double- and triple-slotted configurations result in better performance. Among the various slot configurations in the shapes of U, I, and E, the double-slot antenna containing two rectangular slots fixed adjacent to each other in the vertical position showed dual-band operation at 5.12 GHz and 6.8 GHz, with gains of 4.88 dB and 3.22 dB, respectively. Furthermore, the triple-slot antenna configuration showed high gain and good directivity with a single resonant frequency of around 5 GHz. The simulation is carried out using HFSS software.*

Keywords - *Single-slot, Multiple-slot, Conventional patch antenna, Gain, Directivity, Dual-band.*

1. Introduction

Antennas serve a pivotal role in wireless communication by facilitating electromagnetic signal transmission and reception, providing seamless connectivity for a wide range of devices. Their capacity to alter radiation patterns and maximise signal strength is essential for ensuring reliable data transfer and network coverage. Microstrip patch antennas are a research priority due to their small size, adaptable integration, and ease of fabrication in wireless communication systems. Traditional patch antennas frequently have limits in terms of gain, directivity, and bandwidth, making them less suitable for modern wireless communication systems that require higher performance. Slotted patch antennas excel compared to conventional antennas in terms of gain, directivity, and bandwidth, making them well-suited for the demands of modern wireless applications [1].

The strategic use of slots improves radiation patterns, allowing for higher signal coverage and more efficient communication in a variety of situations. Slots in the patch structure allow for wider bandwidth, which allows slotted patch antennas to operate across a wider frequency range. This feature is particularly useful in applications requiring multi-band or wide-band communication systems [2-5]. These slots alter the radiation pattern, maximizing the signal strength in a particular direction, hence increasing gain and directivity, which is a demand for long-range modern wireless communication systems [6, 7]. Slotted patch antennas can be designed to support dual-polarization or even circular polarization [13, 14]. This feature is beneficial in applications where polarization diversity is required for robust and reliable communication.

Patel et al. [8] proposed a patch antenna with four circular and four-square slots, operating at dual frequency bands of 2.4 GHz and 5.5 GHz, with gains of 1 dBi and 0.26 dBi, respectively, suitable for WLAN applications. Bhavani et al. [9] utilized Defected Ground Structure (DGS) and multiple U cuts in a patch antenna intended to operate at 3.9 GHz and 4.8 GHz, yielding relatively low gains of approximately 1.25 dB and 1.03 dB. Prasanna et al. [10] employed two rectangular slots in a patch, resonating at 2.36 GHz and 3.45 GHz, obtaining gains of 2.34 dB and 2.7 dB, respectively. Additionally, Kaur et al. [11] designed and optimized a dual-band slotted patch antenna using the Differential Evolution (DE) algorithm, enhancing cross-polarization levels at 2.53 GHz and 5.7 GHz with gains of 3.64 dB and 3.84 dB, respectively. Rabnawaz et al. [12] developed a dual-band microstrip antenna for Wi-Fi applications at 2.5 GHz and 5.8 GHz, utilizing slots in the patch and ground plane, resulting in gains of 1.37 dB and 3.9 dB, respectively. Mahmood et al. [16] designed a patch antenna with a simple slot inverted L-shaped protruding probe, and it is operated with dual frequencies of 2.4 and 5.2 GHz with gains of 0.8 and 1.2 dB, respectively.

The use of antennas that function over multiple frequency bands is important due to their diverse applications. The previous research has explored several slot configurations to improve antenna performance for intended wireless applications, especially to achieve dual-band resonance while operating with moderate gain values. The objective of this paper is to improve the gain substantially by incorporating optimized slot configurations into the patch antenna.

This work is not only about conventional slot configurations; apart from that, it is also about systematically designing and examining slot configurations in the shapes U, I, and E in a radiating patch. Furthermore, the study highlights the superior performance of the triple-slot antenna, which achieves high gain at a single resonance frequency of around 5 GHz and exhibits good directivity. This antenna outperforms both single- and multiple-slot antennas in terms of gain, peak directivity, and return loss, showcasing the effectiveness of slot integration for enhancing antenna performance.

This paper is organized as follows: Section 2 describes the design of conventional antennas; Section 3 addresses the design of single-slot antenna and multiple-slot antenna configurations. Results, discussion, and conclusion were addressed in Sections 4 and 5, respectively.

2. Design of Conventional Antenna

Initially, a basic rectangular microstrip patch antenna is designed on an FR-4 epoxy substrate with a dielectric constant of (ε_r=4.4). This patch antenna is designed with a low profile, hence the thickness chosen as h = 1.6 mm. An edge feed technique is used to link a quarter-wave transformer to a conventional patch antenna in order to match the impedance of the 50Ω transmission line that serves as the source of excitation. The parameters of conventional antennas were extracted through the following equations and tabulated in Table 1. The conventional antenna is designed and simulated to radiate at 5.2 GHz. The conventional antenna is shown in Figure 1.

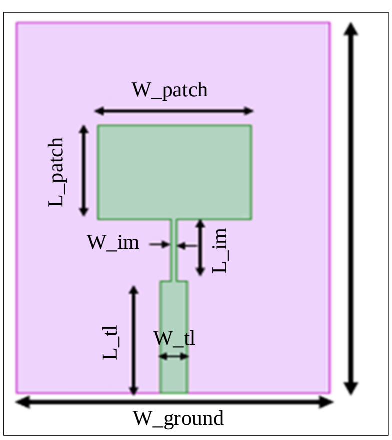

Fig. 1 Conventional antenna

The conventional patch antenna length and width are obtained from the following equations [15].

$$W\_patch = \frac{c}{2f}\sqrt{\frac{2}{\epsilon_r+1}} \tag{1}$$

$$L_{\_patch} = \frac{c}{2f\sqrt{\epsilon_{reff}}} - 2 * 0.412h\frac{(\epsilon_{reff}+0.3)(\frac{W\_patch}{h}+0.264)}{(\epsilon_{reff}-0.258)(\frac{W\_patch}{h}+0.8)} \tag{2}$$

Where, c and f represent the speed of light and operating frequency, here, ∈_r is the dielectric constant, and h is the thickness of the substrate. ∈_reff is effective permittivity and is calculated from Equation (3).

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}(1+12h/w)^{-1/2} \tag{3}$$

$$L\_ground = L\_patch + 6h \;\&$$

$$W\_ground = W\_patch + 6h \tag{4}$$

Where, L_patch and W_patch represent the dimensions of the length and width of the patch antenna, the ground dimensions are obtained from Equation 4, where L_ground W_ground corresponds to the length and width of the ground. Feed line dimensions are represented by (L_tl * W_tl), whereas quarter wave transformer dimensions are represented by (L_im*W_im). Substrate dimensions are the same as the ground dimensions.

Table 1. Dimensions of conventional antenna

Parameters	Value (mm*mm)
Substrate Dimensions	35.9*58.9
L_ground * W_ground	35.9*58.9
L_patch *W_patch	12.56 *17.56
L_tl*W_tl	14.59*3.059
L_im*W_im	7.29*0.723

3. Materials and Methods

In this section, modified single-slot and multiple-slotted antennas are proposed to get better radiation characteristics over conventional antennas. The effect of single and multiple slots is analysed using simulation software.

3.1. Modified Single-Slot Antenna

A rectangular slot of 6mm*2mm in dimension has been incorporated into the conventional antenna to improve its performance. It has been designed using HFSS software, which is depicted in Figure 2.

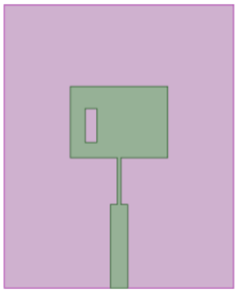

Fig. 2 Single-slot patch antenna

3.2. Modified Multiple-Slot Antenna

Double and triple slots are introduced to compare the performance of slotted antennas, as shown in Figures 3(a) and 3(b), respectively. Further, triple slots are combined to form a U-shaped slot, and the performance of the U-slot antenna is investigated and analysed, as shown in Figure 3(c). In addition to the U slot, I and E slots are created by the proper arrangement of two U slots without altering the dimensions of the U slot, as shown in Figures 3(d) and 3(e). The performance of various slot antennas is analysed using different metrics, viz., gain, return loss, and peak directivity.

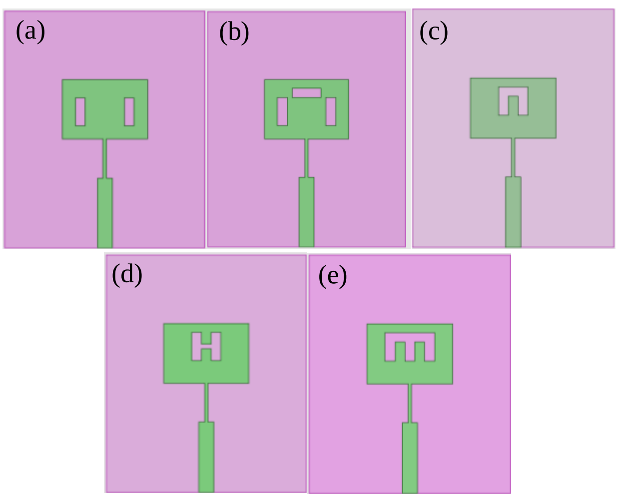

Fig. 3 Design of proposed antennas (a) Double-slot, (b) Triple-slot, (c) U-slot, (d) I-slot, and (e) E-slot.

4. Results and Discussion

The performance of proposed single and multiple slots etched in a conventional antenna is described and analysed in this section in terms of gain, peak directivity, S11, and bandwidth. Figure 4 shows the comparison of the reflection coefficient for a single-slot antenna over a conventional antenna. The reflection coefficient for a conventional antenna is -19.8 dB, and the -10 dB bandwidth is 220 MHz and is resonated at 5.2 GHz. However, when a rectangular single slot is etched on a conventional antenna, the S11 drops down to -38.2 dB at 5.16 GHz. This sharp dip in reflection coefficient is achieved by etching a single slot, which modifies the current distribution and impedance characteristics of a patch antenna, hence better matching with the feed network and reducing reflections. The radiation patterns of conventional and single-slot antennas are shown in Figure 5, where the observed gains for conventional and single-slot antennas are 4.2 dB and 4.7 dB, respectively.

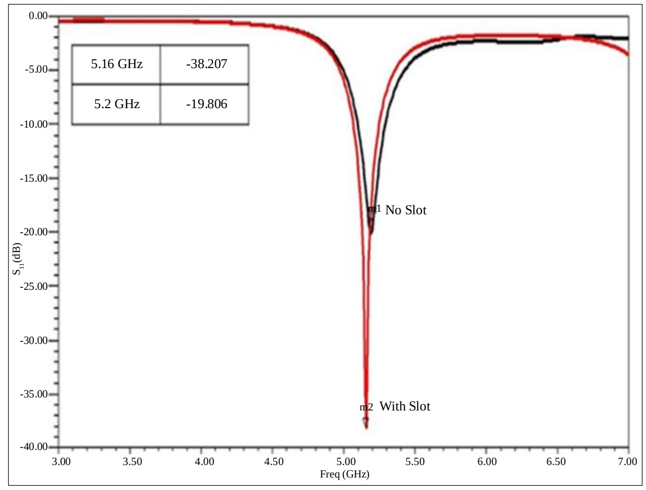

Fig. 4 Reflection coefficient of conventional and single-slot antenna

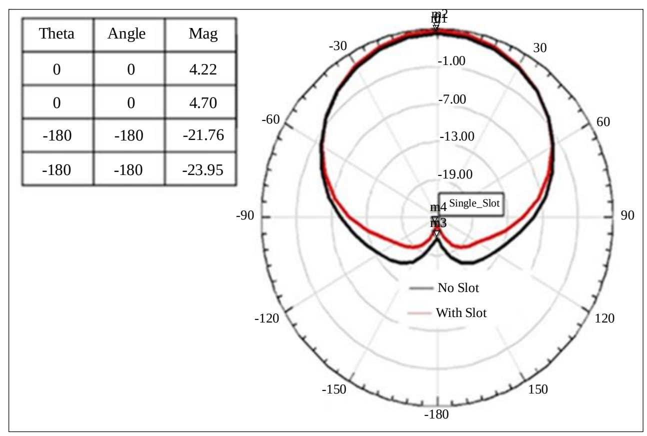

Fig. 5 Radiation pattern of conventional and single-slot antenna

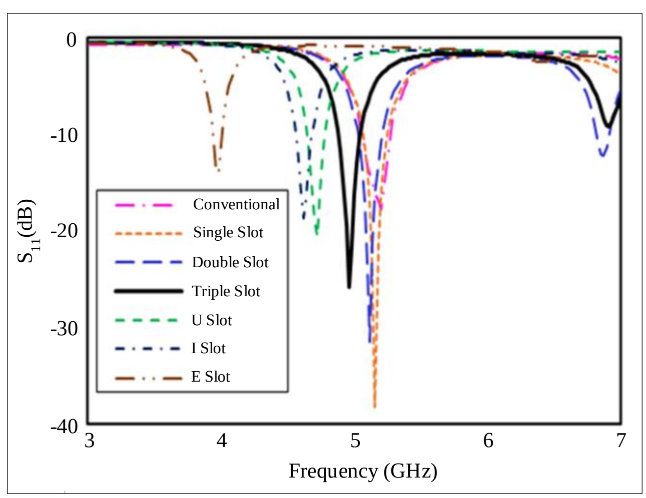

Fig. 6 Frequency vs reflection coefficient curve for various slotted antennas

It is evident from Figure 5 that the reduction in back lobe radiation has decreased from -21.76 dB to -23.95 dB due to the fact that slots couple the electromagnetic waves more effectively; hence, the radiation is more likely to be directional. The performance of different slot configurations in terms of return loss as a function of frequency is evaluated, and corresponding results are shown in Figure 6. From this figure, it is evident that, as the number of slots in a conventional antenna increases, the resonating frequency decreases gradually, which is attributed to the slots creating additional current paths that increase extra capacitance and hence increase the electrical length of the patch antenna. This increment in electrical length decreases the resonant frequency.

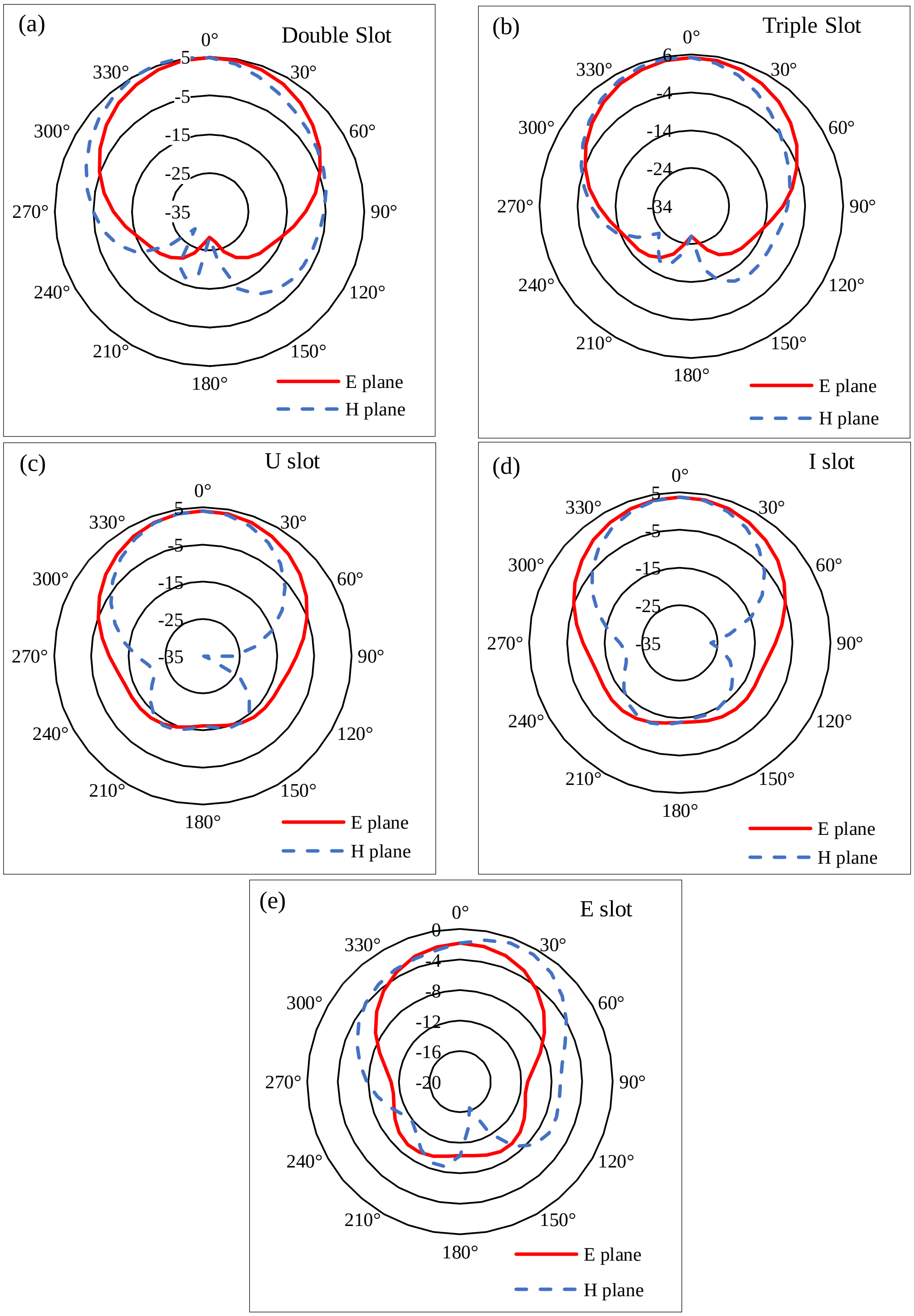

Fig. 7 E and H plane radiation pattern (a) Double-slot, (b) Triple-slot, (c) U-slot, (d) I-slot, and (e) E-slot.

The acceptable impedance match occurs at |S11|>10 dB for all slots of antennas. The double-slot antenna resonates at two different frequencies. The value |S11|>25 dB for single, double, and triple rectangular slot antennas indicates a good impedance match. The radiation patterns corresponding to different slot configurations are plotted, and the results are shown in Figure 7. These depict directivity and gain in the E and H planes of the respective slot configurations. The E-plane (φ=00) and the H-plane (φ=900) are the two orthogonal planes giving needful information about the gain and the directivity. In the single-slot antenna, the E-plane radiation pattern changes and the back lobe level decreases, as seen in Figure 5. However, as the number of slots increases, changes in radiation patterns are observed for double and triple slots, as illustrated in Figures 7(a) and 7(b).

In the case of a double slot antenna, the H plane is asymmetric with respect to the E plane, whereas the H plane is symmetric, and the direction of the H plane tilt is aligned with the E plane in the case of a triple slot antenna. The gain of a double-slot antenna is 4.88 dB and 3.22 dB for the resonating frequencies of 5.12 GHz and 6.88 GHz, respectively and for a triple-slot antenna, the gain is 5.11 dB. Based on these results, it is recommended to use the triple-slot antenna for wireless applications at 5 GHz.

The E-plane radiation pattern becomes closer to omnidirectional as the slot area increases, as we go from triple slot to U slot and from U slot to I slot. Further, this has the consequence of decreasing the directivity, as can be seen in Figures 7(c) and 7(d). The gain then drops to 4.09 dB and 3.71 dB, respectively, which may not be good enough for wireless applications. This is because larger slots can disrupt the current distribution to a greater extent, causing the antenna to radiate more uniformly in all directions. In the case of the E-plane radiation pattern of the E-slot patch antenna, as shown in Figure 7(e), a gain value of -1.8 dB indicates that the radiation pattern is entirely different from the other configurations. Due to the E-slot, severe perturbations occur in the current distribution, leading to destructive interference and poor radiation efficiency, which is not desirable for any applications.

Surface current distribution on a patch antenna is also a significant measure of an antenna's radiation characteristics. The flow of electromagnetic currents along the surface of a patch antenna when triggered by an RF signal is referred to as surface current distribution. The surface current distribution is simulated for single and multiple-slotted antennas. The current distribution on single and multiple-slotted antennas is shown in Figure 8. It describes that at the edges of the patch, the current density is very high except in the E slot patch antenna. These edge currents are the primary sources of electromagnetic wave emission from the antenna. In the E slot patch antenna, the edge current distribution is very low; hence, there is poor radiation among all slotted patch antennas.

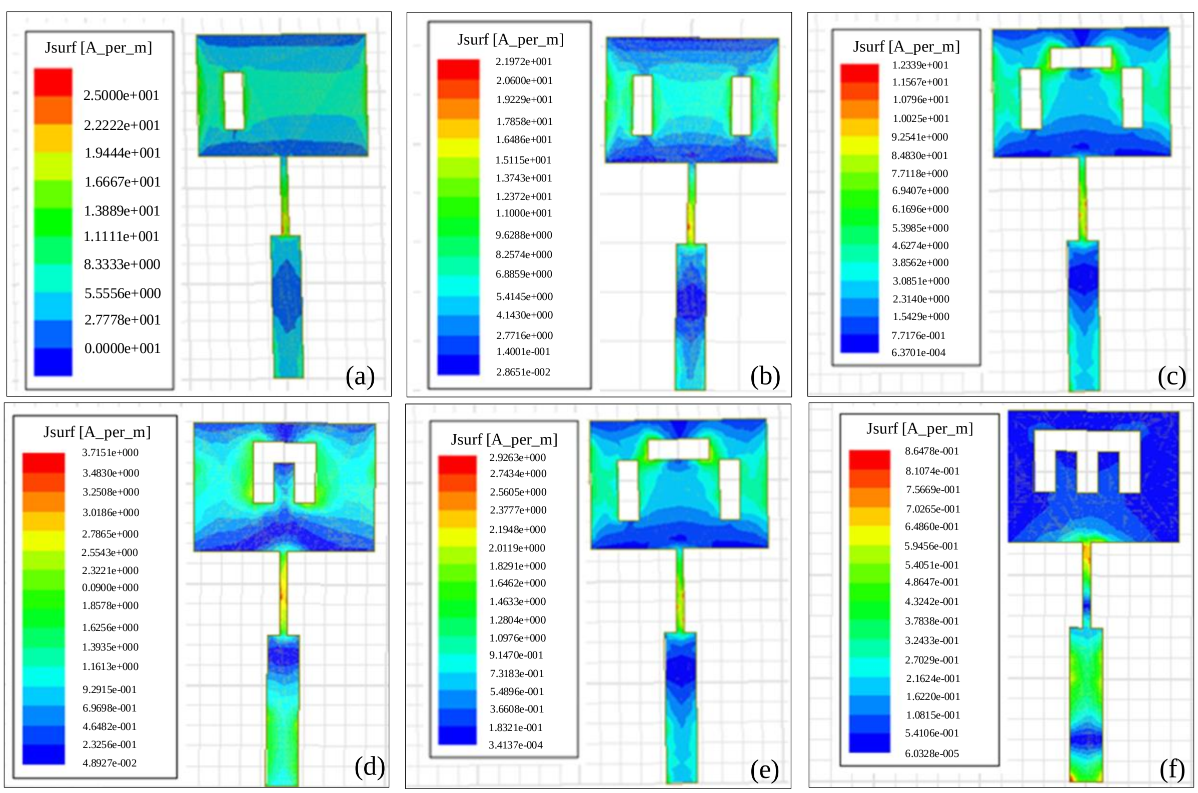

Fig. 8 Surface current distribution on E and H plane radiation pattern (a) Single-slot, (b) Double-slot, (c) Triple-slot, (d) U-slot, (e) I-slot, and (f) E-slot.

The results in Figure 8 clearly indicate that the surface current distribution in a slot patch antenna is more densely spread around the slots. These slots provide extra discontinuities in the metal patch, resulting in increased current concentration around the slot edges. The presence of single and multiple slots in a patch antenna alters the current distribution. Along with single-slots, double and triple-slots are introduced in conventional antennas. Etching of different shapes of U, I and E slot antennas is done. From the above results, the following conclusions are drawn, and the quantitative parameters of each configuration are tabulated in Table 2.

i) The number of slots has a direct effect on the antenna's operating frequency, resulting in a decrease in resonant frequency as the number of slots increases.

ii) Adding slots to a typical antenna changes its gain and peak directivity, demonstrating the effect of slot arrangement on radiation parameters.

iii) Finally, it is concluded that the triple slot gives high directivity and high gain with an acceptable return loss when compared to single, double and multiple slots. The triple-slot antenna radiating at 5 GHz is therefore proposed to serve wireless applications that require high gain.

A single bar chart showing the comparative analysis of each parameter of each configuration of proposed antennas is shown in Figure 9. A comparative analysis of the proposed triple slot patch antenna with existing literature is shown in Table 3.

Table 2. Antenna parameters for slotted patch antenna configurations

Antenna Configurations	S11 (dB)	VSWR (abs)	Gain (dB)	Frequency (GHz)	Bandwidth (MHz)	Fractional BW	Peak Directivity (dB)
Conventional (No Slot)	-19.8	1.29	4.22	5.2	220	4.2	5.3
Single-Slot	-38.2	1.03	4.70	5.16	190	3.68	6.01
Double Slot (Band 1)	-31.3	1.11	4.88	5.12	189	3.63	6.07
Double Slot (Band 2)	-12.1	1.68	3.22	6.88	94	1.36	6.07
Triple Slot	-25.7	1.12	5.11	4.96	164	3.30	6.64
U Slot	-20.97	1.22	4.09	4.71	131	2.78	6.14
I Slot	-18.64	1.32	3.71	4.62	123	2.62	4.80
E Slot	-14.42	1.47	-1.8	3.96	71	1.78	3.95

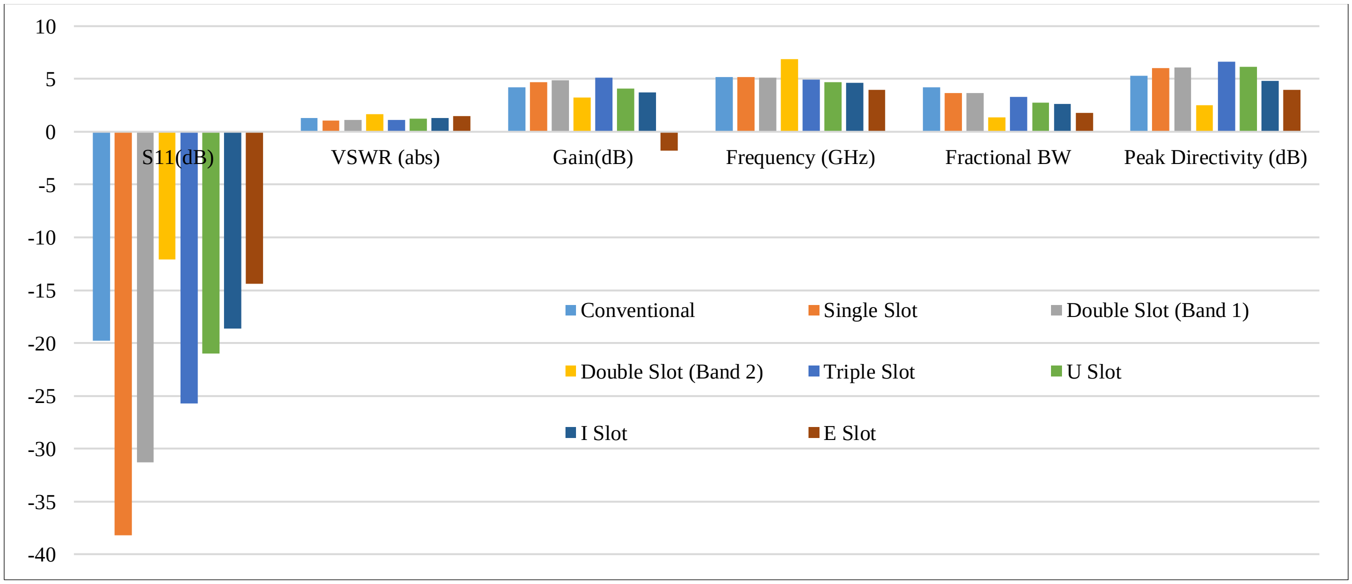

Fig. 9 Bar chart of antenna parameters of all iterations of proposed antennas

Table 3. Comparative study of the proposed antenna with existing antennas

Antenna Literature	Antenna Size (mm)	Operating Frequency (GHz)	Gain (dB)
[8]	29*29	2.4, 5.5	1, 0.26
[9]	15*20	3.8, 4.4, 9.8	1.25,1.02, 2.49
[10]	29*38	2.4, 3.5	1.94,3.31
[11]	7.5*40.7	2.53, 5.77	3.64,3.84
[12]	24*21	2.5, 5.8	1.37, 3.9
[16]	16.35*25.75	2.4, 5.2	0.8, 1.2
[17]	34.5*40	2.45, 3.44	4.8, 3.6
[18]	21*15.3	3.4, 5.5	2.4, 3.5
[19]	7*18	2.46, 4.94	2.31, 3.9
[20]	14*22.5	2.43, 5.52	2.05, 4.52
Double-Slot	12.5*17.5	5.12, 6.88	4.88, 3.22
Triple-Slot		5	5.11

5. Conclusion

This analysis of patch antennas containing slots configured appropriately shows good gain and directivity for a certain configuration. At the same time, other shapes result in moderate gain with operation at two resonant frequencies. The double-slot antenna exhibits dual frequencies of resonance at 5.12 GHz and 6.8 GHz with gains of 4.88 dB and 3.22 dB, respectively.

Further, the simulated results of the triple slot patch antenna showcase a peak gain of 5.11 dB, peak directivity of 6.64 dB, and return loss of 25.7 dB at 5 GHz, marking a significant enhancement over the conventional patch antenna with a 21% gain increment. These findings demonstrate the potential use of these antennas for wireless applications where high gain, directivity, and improved radiation performance are of crucial importance.

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